FINAL REPORT
INSECT FLIGHT: COMPUTATION AND BIOMIMETIC DESIGN

FA9550-05-1-0076

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Research Highlights

Our research has focused on understanding fundamental mechanisms of unsteady aerodynamics in flapping flight. In particular we have focused on dragonfly flight and passive flight of fluttering and tumbling plates in fluid. We use computations, theoretical analyses, and tabletop experiments to unravel the essential mechanisms in these systems. They have yielded new insights into the unsteady aerodynamics and energetics of flapping flight. These new insights offer lessons on designs of efficient small scale flapping wing flight.

- Efficiency of Flapping Flight: optimizing flapping wing motion shows that flapping flight can be as efficient as the best fixed wing motion at small scales.
- Passive Wing Pitching: insects use aerodynamic torque and wing inertial to pitch its wing, and this simplifies the control of the wing orientation and can save energy. The use of passive wing pitching can be used in designing mechanical flapping wing.
- Lift vs. Drag: at small scales and slow speed (low Reynolds number), the wing can use aerodynamic lift or drag to generate thrust at comparable efficiency.
- 3D Navier-Stokes solver: new high order numerical scheme for computing flows coupled to multiple flexible wings. This code can be used to study effect of aeroelasticity.
- Reduced-order Models: studies of freely fluttering and tumbling plates in fluids provides a framework for deducing simple approximation of unsteady fluid forces. These models can be used to construct dynamical simulations of maneuvering flight.

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14. ABSTRACT

Our research has focused on understanding fundamental mechanisms of unsteady aerodynamics in flapping flight. In particular we have focused on dragonfly flight and passive flight of fluttering and tumbling plates in fluid. We use computations, theoretical analyses, and tabletop experiments to unravel the essential mechanisms in these systems. They have yielded new insights into the unsteady aerodynamics and energetics of flapping flight. These new insights offer lessons on designs of efficient small scale flapping wing flight.

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Accomplishments and Results

Optimal Wing Kinematics in Insect Hovering Motions

G. Berman and Z. J. Wang, Journal of Fluid Mechanics, 2007.

We investigate aspects of hovering insect flight by finding the optimal wing kinematics which minimize power consumption while still providing enough lift to maintain a constant altitude. In particular, we study the flight of three insects whose masses vary by approximately three orders of magnitude: fruitfly (*Drosophila melanogaster*), bumblebee (*Bombus terrestris*), and hawkmoth (*Manduca sexta*). We find that the results of this optimization yield kinematics which are qualitatively and quantitatively similar to previously observed data. We also perform sensitivity analyses on parameters of the optimal kinematics to gain insight as to the values of the observed optima. Interestingly, we find that all of the optimal kinematics found here maintain a constant leading edge throughout the stroke, as is the case for nearly all insect wing motions. We show that this type of stroke takes advantage of a passive wing rotation in which aerodynamic forces help to reverse the wing pitch, similar to the turning of a free-falling leaf.

Passive Wing Rotation in Insect Flight

A. Bergou, S. Xu, and Z. J. Wang, Journal of Fluid Mechanics, 2007.

We study the aerodynamic force, torque and power calculated from wing kinematics measured for a tethered dragonfly, *Libellula pulchella*. This is done using two methods – by directly solving the Navier-Stokes equations with a 2D immersed interface method, and by employing a quasi-steady model. Of considerable interest in our results is the passive mechanism of wing pitch reversal, the rapid change of angle of attack near stroke transition. Past work has found that this sudden pitching of a wing plays a key role in lift production during flight, as well as in the ability of an insect to maneuver effectively during flight. By analyzing the power requirements of the wing motion, we find that both the quasi-steady model as well as the direct simulation predict that the wing is turned passively by the fluid force. This is strong and surprising evidence that the motion of the wings can be passive in insect flight. It also suggests a strategy for efficiently pitching a wing in flapping flight.

The Effect of Fore- and Hind Wing Interactions On Aerodynamic Forces and Power in Hovering Dragonfly Flight

Z. J. Wang and D. Russell, Physical Review Letters, 2007.

Dragonflies are four-winged insects which have the ability to control aerodynamic performance by modulating the phase (ϕ) between fore and hind wings. Field and laboratory studies have observed that the two sets of wings beat out of phase during steady flight and in-phase during take-offs. Here we solve the two dimensional Navier-Stokes equations subject to wing motions measured in our tethered experiment, and calculate the aerodynamic force and power over the full range of phase. We find that the fore-hind wing interactions in dragonfly flight does not enhance the vertical force generation, but it can reduce the energetic cost of steady hovering flight. The force and power can vary about $30-40\%$ due to phase variation. The aerodynamic force peaks at $\phi = 0^0$ while the aerodynamic power has a broad minimum at $\phi \sim 160°$. The exact amount of saving must depend on the details of the motion and our 2D approximations, but the power reduction in counter-stroking is essentially due to drag reduction on both wings as they pass each other near the mid-stroke.

Aerodynamic efficiency of flapping flight: analysis of a two-stroke model

Z. J. Wang, Journal of Experimental Biology, 2008.

To fly from point A to point B, a fixed wing travels straight and is most efficient at an angle of attack where the lift to drag ratio is maximum. A flapping wing, on the other hand, follows a zigzagged path, and its efficiency is no longer described by the lift to drag ratio, but depends on the flight path. Here we look for efficient flapping motions in the quasi-steady limit. We identify a minimal model of efficient motions. While a fixed wing has to avoid stall, these flapping solutions make use of dynamic stall and is efficient at angles of attack well above the traditional stall angle. In the 4 dimensional parameter space of our model, the energy function is particularly flat in one direction, and the efficient solutions occupy the top of a continuous ridge.

Immersed Interface Method, Systematic Derivation of Jump Conditions for the Immersed Interface Method in Three-Dimensional Flow Simulation

S. Xu and Z. J. Wang, SIAM Journal of Scientific Computing, 2005.

We systematically derive jump conditions for the immersed interface method to simulate three-dimensional incompressible viscous flows subject to moving surfaces. The surfaces are represented as singular force in the Navier-Stokes equations, which gives rise to discontinuities of flow quantities. We first extend the previous derivation to generalized surface parametrization. Starting from the principal jump conditions, we then derive the jump conditions of all first-, second- and third-order spatial derivatives of the velocity and the pressure. We also derive the jump conditions of first- and second-order temporal derivatives of the velocity. Using these jump conditions, the immersed interface method is applicable to the simulation of three-dimensional incompressible viscous flows subject to moving surfaces, where near the surfaces, the first- and second-order spatial derivatives of the velocity and the pressure can be respectively discretized with third- and second-order accuracy, and the first-order temporal derivatives of the velocity can be discretized with second-order accuracy.

Immersed Interface Method, Implementation and Code Verification

S. Xu and Z. J. Wang, Journal of Computational Physics, 2006.

We implement the immersed interface method to incorporate these jump conditions in a 2D numerical scheme. We study the accuracy, efficiency and robustness of our method by simulating Taylor-Couette flow, flow induced by a relaxing balloon, flow past single and multiple cylinders, and flow around a flapping wing. Our results show that: (1) our code has second-order accuracy in the infinity norm for both the velocity and the pressure; (2) the computational cost is dominated by the pressure Poisson solver and thus the addition of an object introduces relatively insignificant cost; (3) the method is equally effective in computing flow subject to boundaries with prescribed force or boundaries with prescribed motion.

A 3D immersed interface method for fluidsolid interaction

S. Xu and Z. J. Wang, Computer Methods in Applied Mechanics and Engineering, 2008.

This paper focuses on the implementation of an immersed interface method for simulating fluid-solid interaction in 3D. The method employs the MAC scheme, the classical fourth-order RK integration, and an FFT pressure Poisson solver. A fluid-solid interface is tracked by Lagrangian markers. Intersections between the interface and MAC grid lines identify finite difference stencils on which jump contributions to finite difference schemes are needed. To find these intersections and to interpolate jump conditions from the Lagrangian markers to the intersections, parametric triangulation of the interface is used. The velocity of a Lagrangian marker is interpolated directly from surrounding MAC grid nodes with interpolation schemes accounting for jump conditions. A couple of numerical examples demonstrate that (1) the method has near second-order accuracy in the in nity norm for velocity, and the accuracy for pressure is between rst and second order; (2) the method conserves the volume enclosed by a no-penetration boundary very well; and (3) the method can ef ciently handle multiple moving solids with ease.

Personnel Supported

- Z. Jane Wang (P.I.)
- Attila Bergou, PhD candidate in Physics, Cornell University
- Gordon Berman, PhD candidate in Physics, Cornell University
- Sheng Xu, 2003-2006, Postdoctoral Fellow

Publications

- Sheng Xu and Z. Jane Wang, A 3D Immersed Interface Method for Fluid-Solid Interaction', *Computer Methods in Applied Mechanics and Engineering*, **197**, 25-28, 2068-2086 (2008).

- Z. Jane Wang, 'Aerodynamic efficiency of flapping flight: analysis of a two-stroke model', *J. Exp. Biol.*, **211**, 234 (2008) .

- Z. Jane Wang and D. Russel, 'The Effect of Fore- and Hind Wing Interactions On Aerodynamic Forces and Power in Hovering Dragonfly Flight ', *Physical Review Letters*, **99**, 148101(2007).

- Attila Bergou, Sheng Xu, and Z. Jane Wang, 'Passive Wing Rotation in Dragonfly Flight', *Journal of Fluid Mechanics*, **591**, 321-337 (2007).

- Gordon Berman and Z. Jane Wang, 'Energy Minimizing Wing Motion in Hovering Insect Flight', *Journal of Fluid Mechanics*, **582**, 153-168 (2007).

- Sheng Xu and Z. Jane Wang, "An Immersed Interface Method for Simulating the Interaction of Fluids with Moving Boundaries", *Journal of Computational Physics*, 201, 454-493 (2006).

- Sheng Xu and Z. Jane Wang, "Systematic Derivation of Jump Conditions for the Three-Dimensional Immersed Interface Method", *SIAM Journal of Numerical Analysis*, **27** 6, 1948-1980 (2006).

- Z. Jane Wang, "Dissecting Insect Flight", *Annual Review of Fluid Mechanics*, 37, 183-210 (2005).

- Z. Jane Wang, "Insect Flight", *McGraw Hill Year Book of Science and Technology*, 2006.

- Anders Andersen, Umberto Pesavento, and Z. Jane Wang, 'Unsteady Aerodynamics of Fluttering and Tumbling Plates', *Journal of Fluid Mechanics*, 541, 65-90 (2005).

- Anders Andersen, Umberto Pesavento, and Z. Jane Wang, 'Analysis of transitions between fluttering, tumbling and steady descent of falling cards', *Journal of Fluid Mechanics.*, 91-104 (2005).

Honors and Awards, Plenary, Keynote, and Invited Talks (2005-2008)

- Science Fellowship at Radcliffe Institute for Advanced Study, 2007-2008
- Cornell Provost's Award for Excellence in Research, 2005-2006
- Invited lecture, Society of Experimental Biology Annual Meeting, Marseille, France.
- Invited lecture, Neuromechanics of Locomotion, Mathematical Biology Institute, Ohio.
- Invited lecture, American Physics Society, Division of Fluid Dynamics, Annual Meeting, Salt Lake City.
- Keynote talk, SIAM conference on dynamical system, Snowbird, May 2007
- Invited Lectures, CISM (International center for mechanical science), Italy, September 2006
- Invited talk, IMA new direction courses on biological fluid dynamics, MN, June 2006
- Invited lecture, AAAS meeting, mini-symposium on insect flight, March 2006
- Plenary lecture, Prospects of Mathematical Sciences, Academia Sinica at Taipei, December 2005
- Invited talk, Conference on Partial Differential Equations, HongKong, December 2005
- Invited talk, mini-symposium on biological flying and swimming, American Physical Society, Division of Fluids Meeting, November 2005
- Plenary lecture, Mt. Baldy Conference on Scientific Computing, CA, November 2005
- Invited talk, Gordon Conference on Nonliner Sciences, June 2005
- Invited talk, Frontiers in Applied Mathematics, NJIT, May 2005
- Invited talk, Biophysical and Biomechanical Adaptation and Bioinspired Enginnering, Caltech, March 2005.